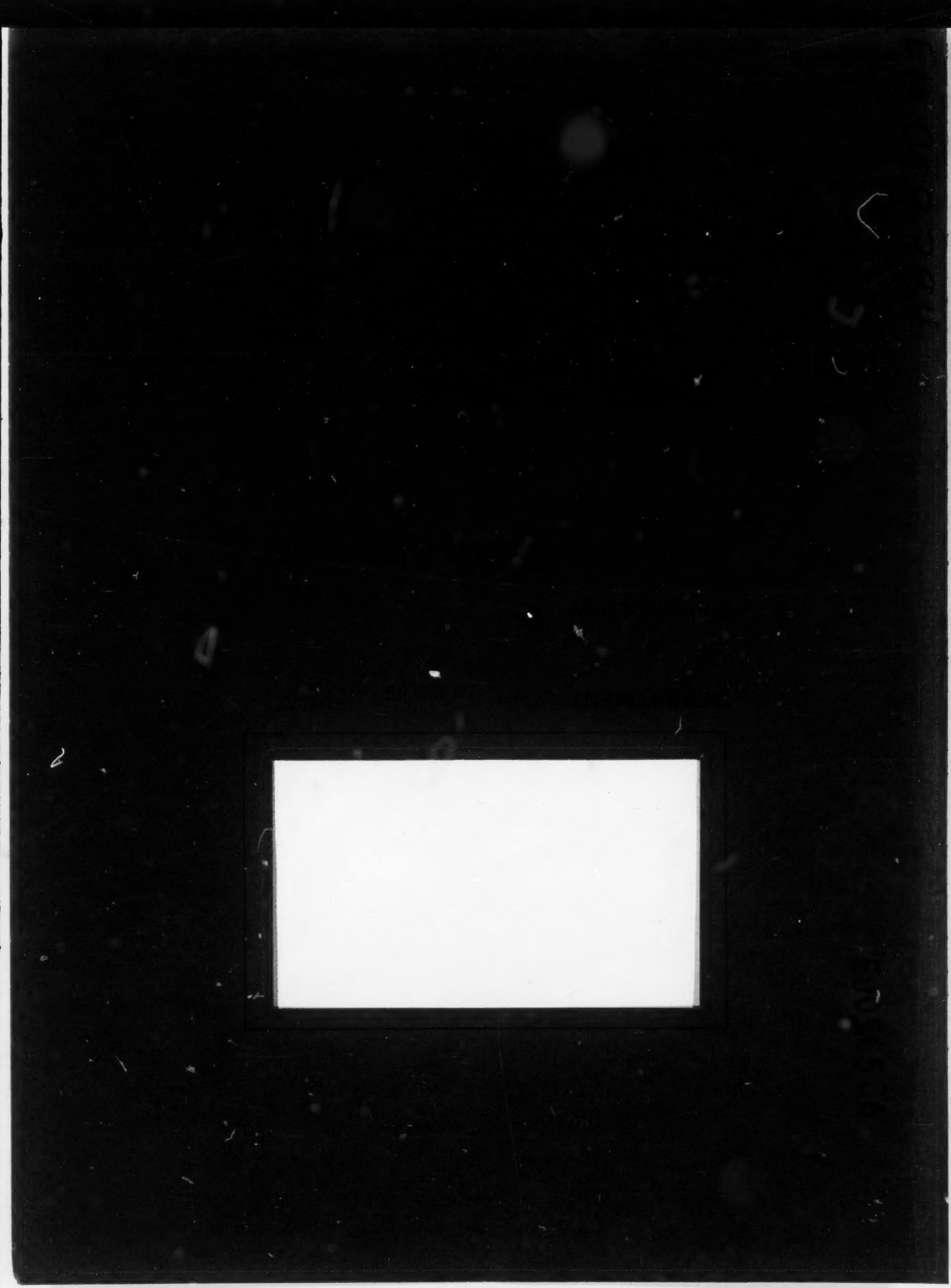
DOCUMENT RESUME

ED 056 526 EM 009 384

AUTHOR	Kleinmuntz, Benjamin
TITLE	Medical Information Processing by Computer.
INSTITUTION	Carnegie-Mellon Univ., Pittsburgh, Pa. Dept. of Psychology.
SPONS AGENCY	National Inst. of Mental Health (DHEW), Bethesda, Md.
REPORT NO	R-70-32
PUB DATE	71
NOTE	43p.
EDRS PRICE	MF-$0.65 HC-$3.29
DESCRIPTORS	Clinical Diagnosis; Computer Assisted Instruction; *Computers; *Electronic Data Processing; Medical Case Histories; *Medical Education; Medical Research; *Medicine; On Line Systems; Simulation

ABSTRACT

The use of the computer for medical information processing was introduced about a decade ago. Considerable inroads have now been made toward its applications to problems in medicine. Present uses of the computer, both as a computational and noncomputational device include the following: automated search of patients' files; on-line clinical data processing; fetal heart rate and fetal electrocardiogram data acquisition; heart auscultation by computer; metabolism data acquisition; pattern recognition by computer; medical diagnosis using the logic of the propositional calculus; computer simulation of diagnostic problem solving; and computer-based medical instruction. (Author/JY)



C. I. P. #169

MEDICAL INFORMATION PROCESSING BY COMPUTER*

Benjamin Kleinmuntz**

Carnegie-Mellon University

Report No. - 70-32

U.S. DEPARTMENT OF HEALTH,
EDUCATION & WELFARE
OFFICE OF EDUCATION
THIS DOCUMENT HAS BEEN REPRODUCED EXACTLY AS RECEIVED FROM THE PERSON OR ORGANIZATION ORIGINATING IT. POINTS OF VIEW OR OPINIONS STATED DO NOT NECESSARILY REPRESENT OFFICIAL OFFICE OF EDUCATION POSITION OR POLICY.

*This paper is to appear as a chapter in The Diagnostic Process, which are the proceedings of a conference held at the University of Michigan, June 17-19, 1970.

**The research reported in this chapter and the time devoted to its writing was supported by NIMH Grants Nos. MH 07722-07 and MH NS 19427-01.

Department of Psychology

MEDICAL INFORMATION PROCESSING BY COMPUTER*

Benjamin Kleinmuntz, Ph.D.

Psychology Department, Carnegie-Mellon University

Pittsburgh, Pennsylvania

Any scientific field that deals with large amounts of data to be analyzed, coordinated and compiled at rapid rates invites the application of high speed data processing techniques. The area of medical information processing is just such a field. Accordingly, scientists have used electronic digital computer technology in this area for a number of years. The computer as an aid in medical information processing has been cast in two quite distinct but complimentary roles; as an instrument of computation and as a noncomputational device. Sometimes the machine assumes both roles and this will be apparent in the following sections.

Patient Files (Computational).

Hospital patient files are made up of a collection of many people's records. For any given patient, the record contains information about him for the duration of his stay in the hospital. Public Health statisticians or administrators and investigators interested in conducting epidemiological studies are frequently concerned with some aspect of the total population of patients. For example, questions involving the incidence of a given diagnosis (in a geographic region or within a hospital), and the association of certain symptoms with particular

---

*This research was supported in part by the National Institute of Mental Health, Grant Nos. MH 07722-07 and MH NS 19427-01.

diseases, can be answered only by referring to the population of patient records.

The efficient search of these records has been made possible by automating hospital record-keeping. Such automation requires a method of standardizing the amount and type of information that is notated on each patient's record. Standardization can be achieved by developing a uniform format in terms of which each physician can input patient data. Along these lines, one investigator (Baruch, 1965; also see Frey, 1969) has developed special computer programs that secure their input information from the user by means of dialogue. These input programs are Socratic in that the computer elicits answers from the clinician, who in turn may address the computer - either orally or with a minimum of button-pushing, or by means of other learned responses. The input device may be located near the computer, or at a remote station.

So that a substantial data base or dictionary may be compiled in computer memory, the cooperation of a large number of hospital personnel is required. Thus it is not sufficient just to have the physician read-in the system signs; it is also necessary to enlist the help of nurses, aides, and pharmacologists. Once such cooperation is attained and the files are compiled, any statistical analysis that can be performed by a clerk can be executed by the computer. Data analysis procedures are available in the form of extensive libraries of "canned" statistical programs.

Statistical analyses of medical records could help in making a clinical diagnosis. The computer, for example, might be presented with the case of a patient exhibiting low grade fever, sore throat, and persistent headaches. By comparing the given symptoms, plus additional history, and laboratory test findings, with similar file cases, the computer might find that in 75% of the

cases in which this configuration of symptoms and signs occurred the diagnosis is a sure case of mononucleosis, the other cases being distributed in other diagnostic categories. Obviously the physician might arrive at the same diagnosis without the aid of a computer, but in cases in which the combination of symptoms presents a complex diagnostic problem, it might be helpful to have immediate access to a large file of medical case histories.

The computer is a valuable aid to the physician also because it can be programmed to take into account the relative frequency of kinds of various diseases and it can arrive at an estimated probability for each of the possibility of diseases that the patient might have. In practice, diagnosis is never a simple, single-step affair. Several stages are involved because each increment of new data about a patient modifies the existing diagnostic picture. The advantage of the computer for this form of sequential decision making lies in its facility for immediate information retrieval and rapid computational capabilities. The drawback of the computer for medical diagnosis, obviously, is that it cannot do a physical examination, read a medical chart or convert narrative information for its use. All information from these sources must be transcribed onto a checklist.

On-line Clinical Data Processing (Computational).

The speed with which a digital computer performs analyses enables these machines to process data while they are being collected. Therefore in addition to searching files, as above, computers can be used to perform simultaneous computations as the data are being input. Such computers are called on-line machines, as distinguished from those that are off-line, where

input-output chores are performed by separate auxiliary equipment. In the early stages of computer technology, off-line machines were necessary because input and output mechanisms, being electro-mechanical, were much slower than the completely electronic storage, processing, and control units of the computer. But lately, computer processing has been synchronized with such auxiliary equipment, performing many operations between successive inputs. Thus, between successive inputs (inputting data is still relatively slow), the computer has time to perform a number of calculations:

The main advantage of on-line computation is that it tends to provide the user with immediate feedback. A fast computer, for example, could calculate the auto- and cross-correlations[1] of an electrocardiogram (ECG) or of an electroencephalogram (EEG) while the record is being taken, thus providing valuable diagnostic information. On-line computation of symptom and sign data, either with a direct patient "hookup"[2] or by having the session on-line[3],

---

[1]The auto-correlation function, which is a relatively recent form of mathematical computation, provides a test of periodicity in a time series recording such as the electroencephalogram. When a periodic signal is present, even though hidden to the eye, this function will identify its periodicity. Cross-correlations permit comparisons of wave or phase characteristics between pairs of EEG recordings.

[2]Direct hookups require a special purpose machine called an analog computer. These machines are equipped to accept electrophysiological data (ECG and EEG) directly.

[3]Facilitation of ongoing interactions between man and the on-line computer requires the ability to have the computer accept and execute several programs concurrently in "a time sharing" fashion.

permits the computer to provide immediate advice about possible further tests to be performed on the individual patients.

This advantage of on-line clinical data acquisition can perhaps be best illustrated by referring to some work going on in electroencephalography (Adey, 1965; Brazier, 1961; 1965). It is in this area of investigation that considerable attention is being given to problems besetting scientists who wish to collect electrophysiological data and to receive almost simultaneous feedback in the form of the data's analysis.

Electroencephalography has its origins in the observation by Caton, in 1875, that spontaneous electrical activity can be obtained from the brain of animals. The relation of this activity to cerebral function was demonstrated by the observation that sensory stimulation could alter the ongoing electrical findings. It was not until 1929 that a German psychiatrist, Hans Berger, demonstrated that the electrical activity of the brain could be recorded from man. The recording of such activity through the intact human skull came to be termed electroencephalography, and after considerable controversy, began to be used in clinical medicine.

Clinical electroencephalography concerns itself mainly with interpreting the EEG for the purpose of aiding the diagnosis of central nervous system disorders. The clinical electroencephalographer examines the record of a patient's EEG for signs of irregularity in the continuously oscillating brain wave forms. This examination consists of a visual analysis and search for specific amplitude, frequency, and wave form variations that conform to

empirically agreed upon signs of pathology (see Figure 1).

Insert Figure 1 about here

Experimental neurophysiology, in contrast to its clinical counterpart, is more concerned with evoking particular wave-forms and manipulating the brain structures that underly the pattern of this electrical activity. And it is here that most of the interesting computer analyses have been conducted. Unfortunately most wave-forms that are currently of greatest interest to the experimental neurophysiologist are of little value to the clinician. But the future of these computer analyses and its applications to EEG recording and interpreting holds considerable promise for the clinician.

Typically the experimentalist records EEG data on special-purpose magnetic tapes and these data are converted from analogue to digital computers - or they are "digitized".[4] This procedure can occur off-line as well as on-line; but when it is off-line the lag between EEG recording and its analysis may be anywhere from several hours to many days. However, all the steps involved in EEG recording, digitization, and interpretation can be synchronized for on-line computation. The advantage of on-line computation, of course lies in the immediate feedback that is thus provided. One such on-line procedure

---

[4]Voltage wave forms such as are obtained in EEG recording cannot be directly read into a digital computer, since they do not contain digits. Also EEG inputs occur as a function of time. Therefore, these data must be converted into digital form, with special attention to preserving the time function.

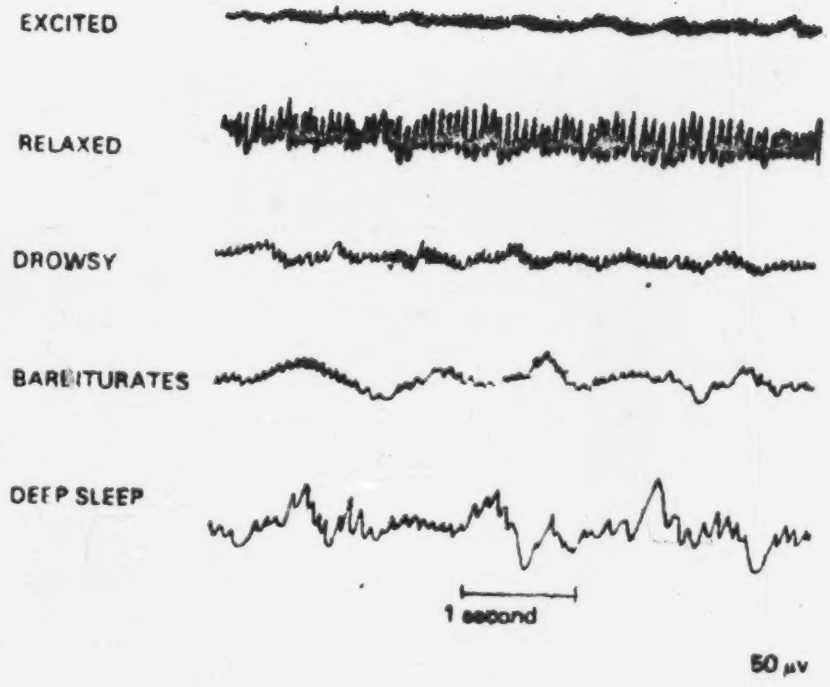


Figure 1: Normal EEG waveforms taken from the intact human skull during various states of the organism

has already been used in the operating room during brain surgery (Goldring, et al, 1964). Here the full benefit of immediate feedback can be seen. The surgeon is given access to an instrument that permits him to operate on the basis of results that are emerging as he works.

As promising as on-line computer analysis of the EEG may seem at the present time, it is essential to emphasize that such computation is far from being generally available to clinicians for sometime to come. It is of considerable interest, also, to note that although the computer has been successfully used to analyze EEG recordings and to classify persons on the basis of these analyses (Walter, Kado, Rhodes, and Adey, 1967), no machine has yet captured the human's skill in recognizing the multitudes of different wave forms. Such pattern recognition is truly still the human's forte.[5]

Fetal Cardiac Data Acquisition (Computational).

A number of investigators are working on automating acquisition and processing of fetal heart rate (FHR) and fetal electrocardiogram (FECG) variables. These measurements have been of great interest to electrocardiographers, especially when they are obtained during vaginal (Hon, 1965; Larks and Larks, 1966) and caesarian delivery (Kendall and Farrell, 1966). FHR and FECG irregularities are among the first signs of fetal distress.

Automating FHR and FECG data acquisition allows continuous data recording, and potentially could provide the attending surgeon with "a quick look"

---

[5] For a report on the advantages and limitations of an on-line data acquisition system in the clinical laboratory and in an intensive care ward, is referred to an essay by Hicks, et al, 1969, and Osborn, et al, 1969, respectively.

appraisal. Such an appraisal may dictate that immediate delivery of the fetus is essential, or it may signify that conditions are normal. Stethoscopic sampling of the FHR, which is presently the most commonly used technique, does not provide a complete picture of these measurements, since it is impossible to record these data continuously throughout labor and delivery. Moreover, with continuous recording techniques, it would be possible to correlate FHR and FECG patterns with various operative procedures, and with different phases of childbirth. But such automation, and the accompanying advantages, are far from being operational at the present time. Unfortunately, current costs, limited computer programming sophistication, and hardware considerations still present problems that await solution prior to realizing such computer system.

Heart Auscultation by Computer (Computational).

Physicians differ widely in their perception and interpretation of heart murmurs obtained by clinical auscultation. Heart auscultation is typically performed by placing a stethoscope on the left lateral position of the patient and listening to the precordium for valvular heart anomalies. Because the diagnosis of heart disease depends on the outcome of auscultation, a group of investigators (Taranta, Spagnuolo, Snyder, Gerbard, & Hofler, 1964) conducted a study in which they tested the accuracy of this method. They demonstrated that experienced physicians differentiate normal from abnormal heart conditions by the method of auscultation with success rates of 4 percent false positive and 37 percent false negative.

These investigators then conducted an automated analysis of

phonocardiograms. The first step in this procedure was to tape record the heart sounds by means of a special-purpose audio-visual recorder.[6] These tapes were next transcribed onto a continuous (analog) linear tape, and were converted for the digital computer. The digitized recording was then submitted to numerous multivariate statistical analyses by computer. The overall success rate was significantly higher (7 percent false positive and false negative) than clinical and tape-recorded heart auscultations.

The prospects for the future are good for providing the surgeon with continuous heart auscultation data during his operative procedure. And these data, when considered together with other electrophysiological recordings, all being analyzed and interpreted almost simultaneously, should add to the clinician's diagnostic accuracy. The costs for such on-line systems are considerable, however, and large time-sharing computers to process these data are still not readily available for routine use. In the meantime, many computations can be performed off-line; and if the diagnostic success rate continues to be consistently higher than that of clinical auscultation, then the computer is an important clinical adjunct even in its present form.

Human Metabolism Data Acquisition by Computer (Computational).

The observation of recurring patterns in the metabolism of humans, particularly as reflected in the urine composition, plays an important part in

---

[6]The same physicians who performed the clinical auscultations listened to these recordings. Their success rate was about equal to that obtained after they had performed the clinical auscultations.

diagnosing the state of the organism at any point in time. Metabolism patterns are affected by many factors, particularly normal diurnal periodicities, normal schedules, and numerous other environmental changes, such as room temperature and position in bed. The problem of acquiring metabolism data from spinal-cord injured quadriplegics is currently being investigated in a multidisciplinary project at the Highland View Hospital in Cleveland (King & Apple, 1966). Although, this project is oriented toward manipulating experimental variables, the value of such data acquisition for clinical decision making should be apparent.

The system is designed so that urine data are collected from a continuous-flow indwelling catheter; and bladder temperature, peripheral temperature, pulse, respiration, and muscle activity are measured by telemetry. Although the system is still not completely automated, such automatic data collection is clearly within view.

The biochemical analysis is automated and consists of transporting the urine sample out of the patient's room to a large cold room where it is weighted and measured for the presence of sodium, potassium, creatinine, chlorine, and nitrogen. The data are presented in analog form and then digitized for computer analysis. Clearly the objective of a fully automated system will be to provide the physician with an arrangement whereby he can obtain almost immediate feedback. From an instrumentation point of view, the major problems encountered in fully automating this system consist mainly of integrating it with the patient, while at the same time designing it to input data that satisfy the requirements of the digital computer. When these human and

hardware problems are resolved, the physician will have access to one other tool to aid him in arriving at an accurate diagnosis.[7]

Pattern Recognition (Computational and Noncomputational).

A pattern is a form which is characterized by a definite arrangement or interrelation of parts. The letters A, B, and C, for example, are alphabetic patterns. ECG and EEG tracings are also patterns. There are two main aspects in programming a computer to recognize patterns: the perceptual and the cognitive. The first of these - beyond which present-day computer technology has not made notable progress - consists of programming the computer to recognize that the same class name should be assigned to different manifestations of the same pattern or form. For example, small circles and large circles must be recognized as circles; and short As, tall As, fat As, and sloppy As must be recognized as an A. Perceptions of this kind are trivial for humans, once they have been taught to differentiate one pattern from another and to assign class names to various patterns. And an electroencephalographer has no more difficulty differentiating between, let us say, alpha and delta rhythms than does a child in discriminating between the letters A and B.

The second, or cognitive, aspect of pattern-recognition programming is concerned with interpreting the identified forms. That is to say, many beginning medical students can learn to differentiate between an EEG alpha and

---

[7]For reports on computer-based monitoring systems and a comprehensive patient monitoring concepts, the reader should see articles Warner, 1969 and Stacy, 1969.

delta rhythm and can be taught to recognize unusual wave-forms such as "spike" or "dome" discharges, but they may need many years of additional experience to interpret (or to learn to attach correct clinical significance) to these recognized patterns. Moreover, understanding the in-context meaning of particular waveform occurrences within an individual's EEG record requires a form of cognitive pattern recognition which is more complex than just perceptual identification.

Generally speaking, even perceptual pattern recognition by computers has proved more difficult than was initially anticipated. This skill of the human to recognize patterns, upon close investigation, turns out to involve many complex processes. One reason for the difficulty in programming the computer to recognize patterns lies in the difficulty the human has in explicating his ongoing process. A human who abstracts a pattern often is unaware of the basis of his classification. Asked to define the pattern he has recognized, the human may point to examples of similar patterns instead of explicating its characteristics. Thus, if pressed the human says he recognized the letter A, or a particular circle, because it resembles an A or a circle. In other words the human's pattern recognition is a consequence of experience or learning, and if asked to introspect about the process he says that he is matching the new pattern with one that he has in mind.

The simplest automatic pattern-recognizing programs are based on a straight-forward matching notion (Green, 1963). They compare the new input with a stored ideal version of each alternative, and the closest match compares the input with a stencil of each letter; the most closely fitting stencil indicates the choice.

But there are difficulties in this simple matching procedure. For while it seems reasonable to store perfect patterns and to retrieve and match these ideals with new inputs, the question of handling inputs of imperfect patterns or variations of the ideal patterns presents a problem. Occasionally this problem can be surmounted. Devices for reading printed numbers from checks get around the problem by creating artificial differences in size and shape between numerals to accentuate the differences. And plausibly, ECG or EEG tracings could be thus accentuated. However, the imperfections and variations are often so large that there is minimal correspondence between inputs and stored ideals. Generally, therefore, pattern recognition by computer has favored methods that analyze inputs.

The strategy usually followed in analyzing inputs has been to select several attributes of the alternative patterns and to characterize the inputs, as well as the alternative patterns, in terms of these attributes. Thus an attribute of hand-lettered characters, for instance, might be number of curves. Each pattern has a particular value of each attribute [for example, R has one curve (and two straight lines)]. The combination of an attribute and its value is called a property, so that R has the property of one curve and two straight lines. In practice, to recognize a given pattern, the computer compares the observed properties of the input object with the stored distributions of values for that pattern. The machine then computes the likelihood that the input object is an instance of stored pattern. There are two such programs that use the strategy of analyzing inputs, which are of potential use in recognizing patterns such as are obtained in medical

settings. These are MAUDE (Morse Automatic Decoder), described by Gold (1959), and Pandemonium, used and described by Doyle (1960, by Selfridge and Neisser (1963), and by Kleinmuntz (1969, 1970).

Many other, more complex pattern-recognition computer programs are being developed (see Fogel, Owens, & Walsh, 1966; Uhr, 1966; 1970); and applications of these programs for medicine are apparent. For example, once the computer learns to recognize patterns of shadows and spots on x-rays, it could be programmed to differentiate diseased from nondiseased chest x-rays.[8] Likewise, once the machine learns to recognize EEG patterns (for example, alpha rhythm, spikes, domes, petit mal variants) it can be taught to undertake the next, or interpretive, phase of EEG reading. And if the error rates can be minimized for both the perceptual and the cognitive performances of these programs, then perhaps computers can become valuable consultants in these areas. The rather unhurried pace of progress in pattern recognition, however, suggests that these future developments are far from imminent.

Logical Reasoning in Medical Diagnosis (Computational and Noncomputational).

Using a combination of symbolic logic (propositional calculus) and probability theory, two investigators (Ledley & Lusted, 1959; Ledley, 1962) demonstrated that the computer could be an aid to the physician in arriving

---

[8]Sterling and Perry (1965) recently described an interesting pattern-recognition program, which is designed to visualize radiation-dose distributions used during radiotherapy. Basically the program provides the therapist patterns of dose distributions resulting from the configurations of treatment conditions.

at a diagnosis and in choosing an optimum treatment plan.

The use of logic for this purpose is closely related to the concept of symptom-disease complexes (SDC). According to these workers, a symptom complex is a list of the symptoms that a patient does and does not possess; a disease complex is a similar list of diseases. An SDC is a list of both symptoms and diseases that a patient does and does not have. As an example of this, consider Figure 2 where two symptoms, S_1 and S_2, and two diseases D_1 and D_2 are presented. Each column represents an SDC, where a unit in the row signifies that the patient has the corresponding symptom or disease and zero signifies that the patient does not have the symptom or disease. Thus the column in the rectangle of Figure 2 represents the SDC of the patient having S_1, not having S_2, having D_1, and having D_2. The columns of this figure represent all conceivable (by applying the truth tables of symbolic logic) SDCs that can be formed from two symptoms and two diseases.

Insert Figure 2 about here

Ledley (1962) uses the phrase "all conceivable SDCs," but then points out that not all of these are possible or actually occur. That is to say, "all conceivable SDCs" as computed by the truth table method does not necessarily correspond to what is possible according to medical knowledge. The effect of medical knowledge on the shape of the truth table matrix is to reduce the totality of all conceivable SDCs to those that are compatible with the assertions embodied in the medical knowledge. Figure 3 represents all possible SDCs for the situation in which application of knowledge has

S_1	1111	1 111	0000	0000
S_2	1111	0 000	1111	0000
D_1	1100	1 100	1100	1100
D_2	1010	1 010	1010	1010

Figure 2: Logical basis for two symptoms, S_1 and S_2, and two diseases, D_1 and D_2.

reduced the logical basis of possibilities.

Insert Figure 3 about here

The preceding description is somewhat abstract (and oversimplified), and therefore it may be helpful to reify it with an illustration. Using the reduced logical basis of SDCs presented in Figure 3, suppose a particular patient presents the following symptom complex: He does not have S_1, but does have S_2, written symbolically, this is

$$\overline{S}_1 \cdot S_2$$

where the "_" bar represents NOT and the dot "." represents AND. To make the diagnosis, consider Figure 3, which contains the reduced basis of all possible SDCs for those columns that include the symptom complex $\overline{S}_1$, S_2. There is one such column (rectangle), and this informs the diagnostician that the patient with this symptom complex has disease complex $D_1\overline{D}_2$. In other words, the diagnosis is that the patient has D_1, but not D_2. These truth table matrixes are stored in the computer, and the machine is programmed to search, detect, and print-out the diagnosis in the form of the logical possibilities. Although a computer is not essential for this storage and retrieval exercise, considerable time and effort are conserved by the use of the machine.

Although such computer analysis may seem elegant at first glance, the fact of the matter is that SDCs are not all-or-none affairs. The problem of diagnosis really revolves about the following question: Given the patient's present symptom-complex, what is the probability that he has a particular

S_1	111	101	0	0
S_2	111	000	1	0
D_1	110	110	1	0
D_2	101	101	0	0

Figure 3: Reduced logical basis resulting from applying medical knowledge to the truth table of Figure 2. The rectangle is the case of a patient having $\overline{S}_1 \cdot S_2$ (see text).

disease complex? The answer to this question requires the application of statistical decision theory. Such application often presents a computational burden that is cumbersome for humans and is a job best left to computers.

Computer Simulation of Clinical Diagnosis (Noncomputational).

Up to this point, the use of computers in medical settings had its primary emphasis on getting a task done. That task is arriving at a diagnosis. An entirely different research strategy has been followed by some investigators (Bellman, Friend, & Kurland, 1965), who are more interested in studying the diagnostic decision process of physicians than they are in developing a computer program that accurately classifies diseases. Some of this research will be discussed in detail here.

It was within the context of complex information processing by computers developed by Newell, et al, (1961; 1971) that we (Kleinmuntz, 1965; 1968; Wortman, 1965) undertook a number of studies involving the diagnostic problem solving of clinical neurologists. The two fundamental assumptions guiding these studies were 1) that clinical decision making is a special instance of problem solving and 2) that problem solving behavior can be studied by computers as a complex information processing phenomenon.

The distinction between the complex information processing approach and numerous statistical decision theory strategies is that the former's goal is to parallel rather closely the consistencies, inconsistencies, errors, and shortcuts of the human diagnostician, whereas the statistical approaches are intended to produce a decision-making system that is an optimal or best possible system. Thus the main distinction is that the latter strategy

strives for optimality and the former for accuracy in reproducing thinking. The advantage of the complex information processing approach is that its emphasis is on simulating the human clinician and as such may yield information that may be useful for modeling him, which in turn could be used as a teaching device.

To learn about neurologists' diagnostic search strategies, we devised a scheme which allowed the clinician to "think aloud". This was a method comparable to the one we used successfully in Q-sorting MMPI profiles (Kleinmuntz, 1963), but yet appropriate to the neurology problem. A variant of the childhood game of "Twenty Questions" fulfilled these requirements. The game is played by having one player, called the experimenter, think of a disease, while the other player, or subject, tries to diagnose the disease the experimenter has in mind. The experimenter can play any of a number of roles: he can pretend, for example, that he is a patient suffering from symptoms x, y, and z; or he could assume the role of the neurologist who is thinking of a particular disorder that is characterized by symptoms x, y, and z. The diagnostician's job in either case is to inquire about the presence of certain symptoms, signs, or biographical data and he may, if he chooses, ask for certain laboratory test results. It is necessary that the experimenter be an experienced neurologist so that he can answer the subject's questions. He must be able to recognize the appropriateness of many symptoms, signs, and laboratory tests that might possibly be relevant for a particular disease.

These games are tape-recorded, and the end product, after appropriate

editing, can be represented by a tree structure (see Figure 4) in which each point, or node, in the tree has exactly one connection to a point closer to the top or root of the tree. The starting point at the top, or the root, of the tree is the subject's first question. All subsequent questions are the tests that are performed at the various nodes of the tree. Each nodal point, then, represents the question asked by the subject or diagnostician; if the experimenter's reply is negative, then there is a branch to the left; if a positive reply is obtained, there is a branch to the right. Unless a diagnosis has been reached each node is connected to exactly two lower nodes and through them to any number of still lower nodes. A path is a collection of lines from the root of the tree to a terminal node and is the schematic representation of the search strategy used by the neurologist to arrive at a diagnosis. In other words, the tree structure is a representation of the diagnostician's solution path from a certain set of givens to the diagnosis.

In order to illustrate this procedure, we present one such game in detail in Figure 4. The diagnostician was given the information that he is to diagnose the case of a 57-year old white female with aching and weakness in the lower extremities.

Insert Figure 4 about here

Inspection of this tree structure discloses that from the point at which the diagnostician asked the first question ("Was this gradual in onset?") until a diagnosis was reached, there were exactly eleven questions or test

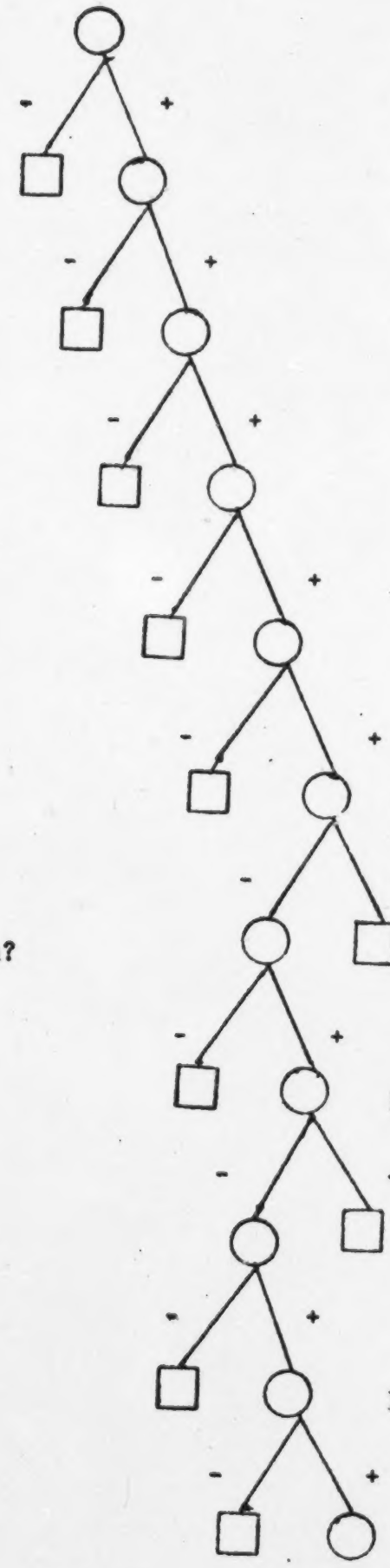

Onset gradual?
Any paraesthesia in her legs?
Any objective sensory signs?
Decreased vibration in her feet?
Is the muscle weakness worse proximally?
Spinal fluid normal?
High protein?
Moderate elevation - let's say between 100 and 200?
Under 100?
Is she diabetic?
Then the diagnosis is Proximal Diabetic Neuropathy.

Figure 4: Fifty-seven year old white female with aching and weakness in the lower extremities.

nodes and ten binary branchings. Of the latter, seven were positive and the remainder were negative branchings. But more important than these descriptive features of the diagram is the fact that we have the diagnostician's solution path, which presumably is related to the way he might function when confronted with a patient exhibiting similar symptoms.

In order to gain a further glimpse of this neurologist's reasoning process, he was instructed during a subsequent session, to state his reasons for asking each of his questions. Table 1 contains the same information that was presented in Figure 4 with the addition of the neurologist's stated reasons. Having the neurologist articulate his reasoning provided us with a rich "thinking aloud" protocol, while at the same time it allowed us to secure a test-retest reliability estimate of the size and structure of the tree structure.

Insert Table 1 about here

There are numerous promising possibilities open to us in the way these data could be best utilized. The most obvious of these uses is to collect a large number of protocols from one neurologist. These protocols would serve as a data-base, which could be stored in the computer, and, along with the clinician's heuristics, would represent one neurologist's method of diagnostic problem-solving. Ideally, the neurologist selected for such representation would be a highly proficient one. But one need not be so delimited. Conceivably, proficient and non-proficient diagnosticians could be simulated and then their strategies compared.

Table 1 - Protocol of a Diagnostician's Questions and Stated Reasons of a Disease Characterized by Aching and Weakness in the Lower Extremities in a 57-year-old White Female (See Figure 4).

Question and Answer at Test node		Stated Reason
Gradual in onset?	(Yes)	It is very important to narrow it down to one of two categories. That is between degenerate or tumor disorders and infections and vascular diseases.
Any paraesthesia in her legs?	(Yes)	This is just to implicate the sensory tracts.
Any objective sensory signs?	(Yes)	This includes decreased position sense which is a posterior column sign usually.
Decreased vibration sense in her feet too?	(Yes)	Both carried in the same column, and I'm just reaffirming this.
Is her muscle weakness worse proximally?	(Yes)	Different diseases give you different proximal vs distal weakness.
Did the lady have normal spinal fluid?	(No)	I want to see if there is increased protein and cells in the fluid and therefore if she has tumor vs inflammatory disease.
High protein?	(Yes)	This is just one of the constituents - cells, protein and perhaps glucose.
Between 100 and 200?	(No)	If it is markedly increased, it could be a tumor.
Under 100?	(Yes)	Normal is up to 45. Therefore, let's think of diabetes.
Is she diabetic?	(Yes)	
Ok, the diagnosis is proximal diabetic neuropathy.	(Yes)	

Individual differences among diagnosticians could also be ascertained by our laboratory procedures. That there are individual differences among diagnosticians in their ability to attain correct decisions is obvious. Not so obvious, however, are ways and means to measure those differences. Using the tree structure approach to diagnostic problem solving, we have been able to demonstrate graphically the existence of individual differences among diagnosticians. A comparison of the trees yielded by experienced and inexperienced neurologists, for example, disclosed that the latters' structures contain many more nodes, more naive questions and search strategies that yield considerably less information per question than those of experienced neurologists.

Finally we can mention a third possible use to which our tree structure approach could be put. Based on the data collected from all proficient neurologists who participated in the diagnostic games, sufficient information has been collected to construct a medical model which resembles optimal diagnostic problem solving. Using the data base of this model, as well as the heuristics for accessing this data base as inputs to a computer, we can utilize the computer as a tutor to students who will sit opposite it. Thus, upon command the machine will print out a set of givens (i.e., fever and headache in a twelve year old), and the student can play the role of the diagnostician. Or the problem can be turned around. Rather than having the computer serve as a tutor and the subjects sitting opposite it, we can arrange the situation so that the computer attempts to achieve a diagnosis, and the expert neurologist will answer its questions. This is perhaps closer to the

situation as it may ultimately exist where the machine acts as a backup diagnostician for the human clinician who may consult it for provisional diagnoses during his own work-up of a patient. In either case, whether the computer is tutor or diagnostician, the implications for its use in medical education, a topic which we will develop further below, is obvious.

Computer-Based Medical Instruction (Noncomputational).

The idea of programmed and computer-based instruction has its roots in research with "teaching machines". Programmed instruction is an educational technique in which a series of instructional materials or items is presented to the student, who must select a correct alternative or fill in a missing answer. The distinguishing feature from conventional instruction is that the program is designed to provide the student immediate feedback from which he can determine whether his answer was right or wrong. The device by which programmed instruction is conducted is called the Teaching Machine. The latter may range in complexity from textbooks with special page format (to allow feedback), to elaborate electromechanical machines in which the program may be under the control of a digital computer.

Programmed instruction is among other things a response to the challenge of providing for individual differences among learners. A properly programmed tutoring device provides each student with the opportunity to work at his own pace, at the same time allowing him to make as few or as many errors as are necessary for him to learn the material completely. Moreover, such automated instruction relieves the human teacher of his routine, repetitive, and drill-master role, thus permitting him to concentrate more on the motivational,

social, and inspirational aspects of teaching.

The application of data processing and computer technology to the functioning of such programmed instruction is a relatively recent development (see Rath, Andersen, & Brainerd, 1959; Silberman & Coulson, 1962) when compared to the idea of an automatic tutor (see Pressey, 1926; Skinner, 1958). This idea has only recently materialized in the installation of computer-linked typewriter input stations in classrooms and laboratories for faculty and student use. Among the more significant computer-based instructional programs currently being developed outside the medical field are the following (Goodlad, O'Toole, & Tyler, 1966): a program that teaches students to count in the binary-number system and to add, subtract, multiply, and divide and, further, to convert from decimal numbers to binary ones and from binary to decimal numbers (Rath, et al, 1959); a special program of feedback messages designed to provide computer programmers with knowledge of where they made errors in their programs (Perlis, 1959; 1963); an elementary school mathematics program (Suppes, 1965); and PLATO (Programmed Logic for Automatic Teaching Operations), a general-purpose teaching machine system. Since the PLATO system is most closely related to computer-aided research currently being conducted in medical education, we will dwell in some detail on this program (Alpert & Bitzer, 1970; Bitzer & Easley, 1965) before discussing computer-aided medical instruction.

At the Coordinated Science Laboratory of the engineering department at the University of Illinois, a group of scientists have been developing PLATO. The PLATO system utilizes a computer as the central control element for teaching a number of students simultaneously, while allowing each student to proceed

through the lesson material independently. The system provides for communication in two directions. Each student is provided with an electronic key set as a means for responding to the computer's queries and a television screen for viewing information selected by the computer. There are two sources of information which are usually displayed on the student's television screen: a bank of slides prestored in an electronic slide selector under the control of the computer and a computer-controlled storage tube that permits plotting (at each of many student stations) diagrams, symbols, and words on the student's storage tube.

PLATO has two systems of teaching methods, a "tutorial logic" and an "inquiry logic." The first of these is designed to lead the student through a fixed sequence of topics and provides branching contingencies that depend on the student's speed of learning. The system first presents facts and examples, as is illustrated in Figure 5, and then poses problems covering the material presented. The student selects answers and, when he is ready, asks PLATO for feedback. When he finds the problems too difficult he may choose to branch to easier material. The lesson material is organized in two sequences, the main sequence consisting of the minimum material that must be used by all the students, and the "help" sequence that is designed for students who have difficulty with questions in the main sequence.

The student begins by viewing test material in the main sequence. When he has completed reading a page of text, he pushes the button labeled CONTINUE (see Figure 5) and thus proceeds to the next page, or he can return to the preceding page of text by pushing the button labeled REVERSE. Generally,

students proceed through the lesson material by using the following logic buttons provided to them on a keyset: RENEW, ERASE, AHA, JUDGE, REVERSE, HELP AND CONTINUE.

Questions are answered by having the student type the appropriate responses with the use of buttons similarly labeled to those of a typewriter.

Insert Figure 5 about here

His answer appears on a cathode ray tube almost simultaneously. The student then may push the JUDGE button, and the computer determines the acceptability of the answer by printing out OK or NO next to the answer. By using the ERASE button, the student can remove incorrect answers. He can push the HELP button if he has difficulty with the question, and this would take him into a help sequence that pertains to the question.

The lesson materials are prepared for the tutorial logic by arranging them in a set of slides with at least one help slide for each question in the main sequence. Also a parameter tape is prepared, which contains the answers to the questions, their location on the slide page, and the order in which the slides are logically connected. Finally, error categories must be specified (for error detection) and a list made of monitored problems and their criteria for evaluation.

The inquiry-teaching logic system permits dialogues between the student and the computer. This system came about as a result of an interest in giving the student even more control of the way he learns than the tutorial system

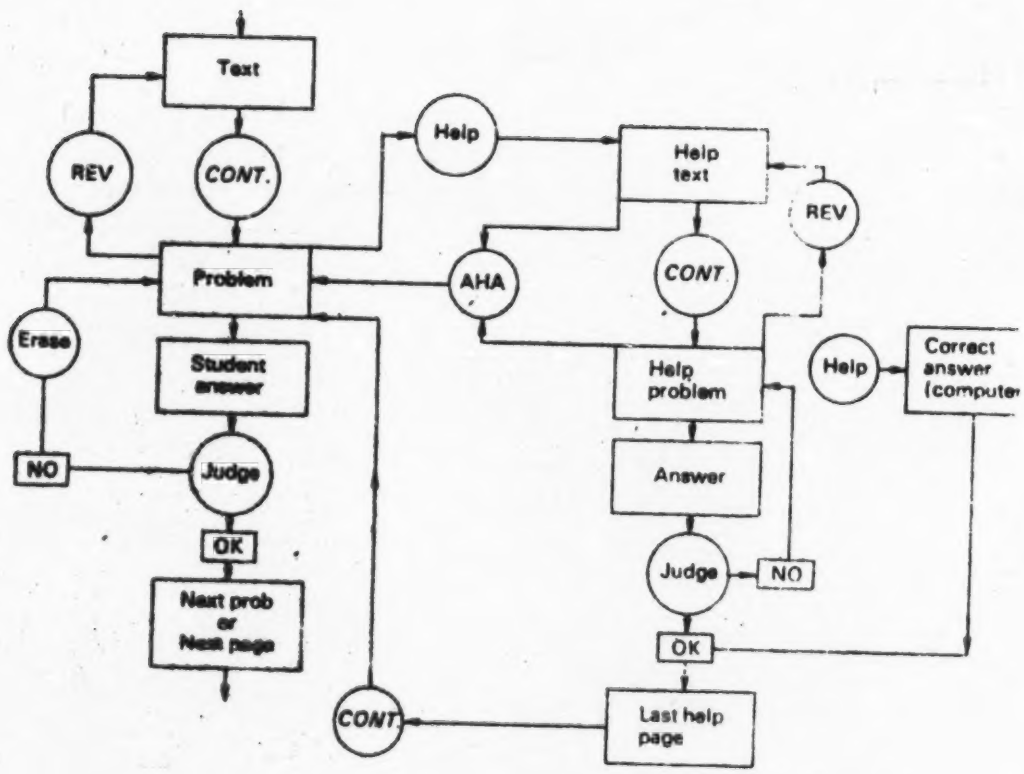


Figure 5: A flow-chart of the tutorial teaching logic. See text for a key to the abbreviations. (From Bitzer, 1965).

permits. The inquiry system allows the student to ask questions of the computer. Typically, in a lesson by this system, general problems are presented to the student. To solve them he must request and organize appropriate information from the computer. The student may be asked to demonstrate his achievement by answering questions and he may also ask questions within a given range of possibilities in order to obtain information.

The innovation of the inquiry logic is that this system provides the student a syntax by which he can ask questions about the lesson he is studying. Thus, for example, in the tutorial logic, the student communicates with the computer either with one of the control requests (that is, "Turn the page"; "Give me help"; "Judge my answer"), or composes short answers that usually must match one of the alternative stored responses. If he types a question such as "What is a coefficient?" the computer might respond with a NO, since it treats his response as an answer. The inquiry logic system, on the other hand, provides the student with the syntax and hence with the opportunity to ask such questions.

This syntax essentially requires that the student ask questions in a specific coded format that permits retrieval of information stored in the computer. One example given by the originators of the system (Bitzer & Easley, 1965, p. 98) is as follows: The student in a teaching program for nurses who would like the answer to the question "What's the effect of administering nitro-glycerine on the heart rate of the patient?" must type the coded format for the following sequence of phrases: "Return patient to original state"; "Give drugs"; "Select nitroglycerine"; "Check condition of patient, vital signs,

pulse rate" (at this point the computer answers the question originally posed).

Similarly several researchers at Bolt, Beranek, and Newman (Feurzeig, Munter, Swets, & Breen, 1964; Swets & Feurzeig, 1965) have developed a computer teaching system and applied it to a problem in teaching medical diagnosis. This system is designed to enable the medical student to augment his experience and his diagnostic skill.

The Bolt, Beranek, and Newman computer program, called the "Socratic System" because of its inquiry format, states a problem (that is, a medical history and a request for a diagnosis) to a student and engages him in "conversation" while he solves the problem. The conversation, of course, is accomplished through the use of an electric typewriter[9] connected to, and controlled by, the computer. The student types a question or an assertion and the machine types back a response - an answer, a comment, or another question. This conversation is executed by supplying the student with a list specifying the vocabulary for the problem. During the session, the student's questions and declarations must be selected from the terms on this list.

The vocabulary can be extensive, and the student is allowed considerable freedom in his approach to solving the problem. He can specify the information he wants and can make assertions regarding the solutions. The system records the information given to the student and answers each of his questions by

---

[9]For a discussion of some of the problems to be faced in designing a computer-based tutor to deal with written and spoken language, see Spolsky (1966).

typing one or more replies from a prespecified set of responses. At any point in time, the computer response depends on what has just been said and on everything that preceded it. Thus the system carries on a tutorial dialogue with the student, one in which interesting contingencies may be developed.

Computer-aided teaching of medical diagnosis, which also has been tried in at least two other studies (Entwisle & Entwisle, 1963; Kirsch, 1963), raises many interesting possibilities for introducing programmed instructional techniques into the medical school curriculum. The clinical experience of medical students is necessarily restricted by the variety of case material available to them and their limited exposure to live patients. Thus, a student may not see any cases of a particular disease during his school years, and some cases he will encounter in his later practice of medicine may differ significantly from the classical or textbook cases. The student's "probability matrix", built up from his personal experience with a limited number of cases, may differ considerably from a matrix that is based on a large number of cases. Practice with programs like the one previously described may permit students to enlarge their probability matrixes.

These computer programs, then, are capable of generating a vast number of hypothetical patients beckoning to be "examined" by inexperienced medical students. The limited usefulness of these programs must nevertheless be recognized. The medical student is not able to view the "acutely prostrated" patient; he gains no experience in obtaining heart auscultation, and generally,

he conceptualizes, rather than practices, medicine. Moreover, the artificial setting of the man-machine interaction does not drive home the lesson of the "real-life" consequences of performing an inappropriate procedure, nor does it confront the neophyte physician with the reality of the discomforts - physical and economic - that accompany his selection of particular laboratory tests or exploratory procedures. But then again, these disadvantages must be weighed against the advantages of the added experience he gains that may otherwise be unavailable to him.

Summary and Conclusion

The use of the computer for medical information processing was introduced about a decade ago. Considerable inroads have now been made toward its applications to the problems in medicine. The future of the computer as an information machine and decision maker in clinical areas is limited only by human ingenuity. There seems to be no lack of such ingenuity in developing the software and hardware that are essential for its usefulness to the clinician. How far or how quickly these developments will advance is difficult to predict; but some of promising present uses suggest that an interesting decade is ahead.

Present uses of the computer, both as a computational and noncomputational device include the following: automated search of patients' files; on-line clinical data processing; fetal heart rate and fetal electrocardiogram data acquisition; heart auscultation by computer; metabolism data acquisition; pattern recognition by computer; medical diagnosis using the logic of the propositional calculus; computer simulation of diagnostic problem solving; and computer-based medical instruction.

References

Adey, W. R. Computer analysis in neurophysiology. In R. W. Stacy, and B. D. Waxman (Eds.), Computers in biomedical research. Vol. 1. New York: Academic Press, 1965, Pp. 223-263.

Alpert, D. and Bitzer, D. L. Advances in computer-based education. Science, 1970, 167, 1582-1590.

Baruch, J. J. Hospital automation via computer time-sharing. In R. W. Stacy and B. D. Waxman (Eds.), Computers in biomedical research. Vol. 2, New York: Academic Press, 1965, Pp. 291-312.

Bellman, R., Friend, M. B. and Kurland, L. Simulation of the initial psychiatric interview. Behavioral Science, 1966, 11, 389-399.

Bitzer, D. L., and Easley, J. A. Jr. Plato: A computer controlled teaching system. In M. A. Sass and W. D. Wilkinson (Eds.), Symposium on computer augmentation of human reasoning. Washington, D. C.: Spartan Books, 1965, Pp. 89-103.

Brazier, M. A. B. Introductory comments. Electroencephalographic and Clinical Neurophysiological Supplement, 1961, 20. 2-6.

Brazier, M. A. B. The application of computers to electroencephalography. In Stacy, R. W. and Waxman, B. D. (Eds.), Computers in biomedical research. Vol. 1, New York: Academic Press, 1965, Pp. 295-315.

Doyle, W. Recognition of sloppy, hand-printed characters. Proceedings of the Western Joint Computer Conference, 1960, 17, 133-142.

Entiwsle, G. and Entwisle, D. R. The use of a digital computer as a teaching machine. Journal of Medical Education, 1963, 38, 805-812.

Feurzeig, W., Munter, P., Swets, J., and Breen, M. Computer-aided teaching in medical diagnosis. Journal of Medical Education, 1964, 39, 746-754.

Fogel, L. J., Owens, A. J., and Walsh, M. J. Artificial intelligence through simulated evolution. New York: Wiley, 1966.

Frey, H. S. An on-line graphic inquiry system for analysis of tumor registry data. In Stacy, R. W. and Waxman, B. D. (Eds.), Computers in biomedical research. Volume 3, New York: Academic Press, 1969, Pp. 87ff.

Gold, B. Machine recognition of hand-sent Morse code. IRE Transactions on information theory, 1959, 2, (pt. 5), 17-24.

Goldring, S., Kelly, D. L. Jr., and O'Leary, J. L. Somatosensory cortex of man as revealed by computer processing of periphally evoked cortical potentials. Transactions of the American Neurological Association, 1964, 89, 108-111.

Goodlad, J. I., O'Toole, J. F. Jr., and Tyler, L. L. Computers and information systems in education. New York: Harcourt, 1966.

Green, B. F. Jr. Digital computers in research: An Introduction for behavioral and social scientists. New York: McGraw-Hill, 1963.

Hicks, G. P., Evenson, M. A., Gieschen, M. M. and Laison, F. C. On-line data acquisition in the clinical laboratory. In Stacy, R. W. and Waxman, B. D. (Eds.), Computers in biomedical research. Vol. 3, New York: Academic Press, 1969, Pp. 15ff.

Hon, E. H. Computer aids in evaluating fetal distress. In R. W. Stacy and Waxman, B. D. (Eds.), Computers in biomedical research. Vol. 1, New York: Academic Press, 1965, Pp. 409-437.

Kendall, B. and Farrell, D. M. Observation of fetal heart rate during caesarian section. In K. Enslein and J. F. Winslow (Eds.), Data acquisition and processing in biology and medicine. Vol. 4, London: Pergamon Press, 1966, Pp. 203-211.

King, P. and Apple, H. Computer-oriented study of human metabolism. In K. Enslein and J. F. Kinslow (Eds.), Data acquisition and processing in biology and medicine. Vol. 4. London: Pergamon Press, 1967, Pp. 23-36.

Kirsch, A. D. A computerized medical training game as a teaching aid. In K. Enslein (Ed.), Data acquisition and processing in biology and medicine. Vol. 2, New York: Macmillan, 1964, Pp. 139-147.

Kleinmuntz, B. A portrait of the computer as a young clinician. Behavioral Science, 1963, 8, 154-156 (a).

Kleinmuntz, B. MMPI decision rules for the identification of college maladjustment: A digital computer approach. Psychological Monographs, 1963, 77, (Whole No. 577, 14) (b).

Kleinmuntz, B. Personality test interpretation by digital computer. Science, 1963, 139, 416-418 (c).

Kleinmuntz, B. Diagnostic problem solving by computer. Japanese Psychological Research, 1965, 7, 189-194.

Kleinmuntz, B. Formal representation of human judgment. New York: Wiley, 1968.

Kleinmuntz, B. Clinical information processing by computer: An essay and selected readings. New York: Holt, Rinehart and Winston, 1969.

Kleinmuntz, B. Clinical information processing by computer. In New Directions in Psychology 4, Pp. 123ff, New York: Holt, Rinehart and Winston, 1970.

Larks, S. D. and Larks, G. G. Acquisition and processing of fetal cardiac data: electrical axis of the fetal heart. In K. Enslein and J. F. Kinslow (Eds.), Data acquisition and processing in biology and medicine. Vol. 4, London: Pergamon Press, 1966, Pp. 191-202.

Ledley, R. W. Advances in biomedical science and diagnosis. In H. Borko (Ed.), Computer applications in the behavioral sciences. Englewood Cliffs, N.J.: Prentice-Hall, 1962, Pp. 490-521.

Ledley, R. S. and Lusted, L. B. Reasoning foundations of medical diagnosis. Science, 1959, 130, 9-22.

Lusted, L. B. Computer techniques in medical diagnosis. In R. W. Stacy and B. Waxman (Eds.), Computers in biomedical research. Vol. 1. New York: Academic Press, 1965. Pp. 319-338.

Lusted, L. B. Introduction to Medical Decision Making. Springfield, Illinois: Charles C. Thomas, 1968.

Newell, A., Shaw, J. C., and Simon, H. A. Empirical explorations of the Logic Theory Machine. Proceedings of the Western Joint Computer Conference, 1957, 11, 218-230.

Newell, A., Shaw, J. C., and Simon, H. A. The elements of a theory of human problem solving. Psychological Review, 1958, 65, 151-166.

Newell, A. and Simon, H. A. Computer simulation of human thinking. Science, 1961, 134, 2011-2017.

Newell, A. and Simon H. A. An information processing theory of human problem solving. (Manuscript in preparation, to be published 1971).

Osborn, J. J., Beaumont, J. O., Raison, J. C. A., and Abbott, R. P. Computation for quantitative on-line measurements in an intensive care ward. In Stacy, R. W. and Waxman, B. D. (Eds.), Computers in biomedical research, Vol. 3, Pps. 207ff, New York: Academic Press, 1969.

Perlis, A. G. Research and development in programming study assignments. Progress Report, Computer Center, Carnegie Institute of Technology, July, 1959.

Perlis, A. G. Personal communication, 1963.

Pressey, S. L. A simple apparatus which gives tests and scores and teaches. School and Society, 1926, 23, 586.

Rath, G. J., Andersen, N. S., and Brainerd, R. C. The IBM research center teaching machine project. In E. H. Galanter (Ed.), Automatic teaching: The state of the art. New York: Wiley, 1959, Pp. 117-130.

Selfridge, O. and Neisser, U. Pattern recognition by machine. In E. A. Feigenbaum and J. Feldman (Eds.), Computers and thought. New York: McGraw-Hill, 1963, Pp. 237-250.

Silberman, H. F. and Coulson, J. E. Automated teaching. In H. Borko (Ed.), Computer applications in the behavioral science. Englewood Cliffs, N.J.: Prentice-Hall, 1962, Pp. 308-355.

Skinner, B. F. Teaching machines. Science, 1958, 128, 969-977.

Spolsky, B. Some problems of computer-based instruction. Behavioral Science, 1966, 11, 487-496.

Stacy, R. W. The comprehensive patient-monitoring concept. In Stacy, R. W. and Waxman, B. D. (Eds.), Computers in biomedical research, Vol. 3, Pps. 253ff, New York: Academic Press, 1969.

Sterling, T. D. and Perry, H. Computation of radiation dosages. In R. W. Stacy and B. Waxman (Eds.), Computers in biomedical research. Vol. 1, New York: Academic Press, 1965, Pp. 439-464.

Suppes, P. Computer-assisted instruction in the schools: Potentialities, problems, prospects. Stanford, Calif.: Institute for Mathematical Studies in the Social Sciences, Stanford University Press, 1965.

Taranta, A., Spagnolo, M., Snyder, R., Gerbarg, D. S. and Hofler, J. J. Auscultation of the heart by physicians and by computer. In K. Enslein (Ed.), Data acquisition and processing in biology and medicine. Vol. 3, New York: Macmillan, 1964, Pp. 23-52.

Uhr, L. Pattern recognition. New York: Wiley, 1966.

Uhr, L. Pattern recognition, concept formation and learning. (Manuscript in preparation: personal communication). 1970.

Walter, D. O., Kado, R. T., Rhodes, J. M. and Adey, W. R. Electroencephalographic baselines in astronaut candidates estimated by computation and pattern recognition techniques. Unpublished paper by the Space Biology Laboratory of UCLA, 1967.

Warner, H. R. Computer-based patient monitoring. In Stacy, R. W. and Waxman, B. D. (Eds.), Computers in biomedical research, Vol. 3, Pp. 239ff, New York: Academic Press, 1969.

Weizenbaum, J. ELIZA-A Computer program for the study of natural language communication between man and machine. Communications of the ACM, 1966, 9, 36-45.

Wortman, P. M. Representation and strategy in diagnostic problem solving. Human Factors, February, 1966, 8, 48-53.